1. PI and Co-I Names and Affiliations

PI: W. Wiscombe (NASA/GSFC)

Funded co-Is: F. Evans (Univ. of Colorado), A. Marshak (Univ. of Maryland), R. Pincus (Univ. of Wisconsin)
Unfunded co-Is: R. Cahalan (NASA/GSFC), A. Davis (Los Alamos Nat. Lab)

2. Title of Research Grant

Modeling of Cloud Liquid Water Structure and the Resultant Shortwave Radiation Field Using ARM and Landsat Data

3. Scientific Goals of Research Grant

Our ARM Research Grant aims to improve theoretical understanding of radiation processes in real clouds. Our end-to-end effort ranges from sophisticated statistical analysis of ARM and other cloud data, to semi-empirical modeling of the 3D distribution of cloud liquid water, to performing 3D shortwave (SW) radiative transfer studies and studying the SW spectra that ARM measures. The components of our program can be summarized as follows:

- apply state-of-the-art statistical analyses to ARM and other cloud data to improve our semi-empirical models of 3D cloud liquid water fields and extend them to all naturally occurring *liquid* cloud types at SGP and TWP; particular effort goes toward modeling broken cloud correctly; data sources like the ARM radar, microwave radiometer, and Micropulse Lidar, Landsat, and Cloud Resolving Models (CRMs), are used to guide the development of, and parameterize, these more general cloud water models;
- based on those semi-empirical cloud water models, perform 3D Monte Carlo and SHDOM radiative transfer calculations of the radiance and flux fields, with particular emphasis on simulating, and learning how to design for maximum benefit, observing systems like that in ARESE;
- *statistically* compare our simulated radiance/flux fields with observed radiance/flux fields from (a) ARM SGP and TWP instruments, and (b) Landsat;
- continue to seek simple ways to generalize the “independent pixel approximation (IPA)” method and our own “non-local IPA” method to better approximate 3D radiative transfer results.

4. Accomplishments

• *Cloud-Vegetation Interaction.* Developed a new technique to retrieve cloud optical depth for broken clouds above green vegetation using ground-based zenith radiance measurements [JP 8, 10].

• *Horizontal radiative fluxes in clouds.* Developed a theory of horizontal photon transport for conservative and non-conservative scattering [JP 11]. Applied this theory to estimate the applicability of the IPA for absorbing wavelengths [JP 2].

• *New radar/microwave radiometer cloud retrieval algorithm*. Developed a liquid cloud microphysics retrieval method for ARM cloud radar based on Bayes' theorem, which uses prior knowledge about cloud microphysics and accounts for uncertainties in the observed data.

• *3D stochastic cloud model.* Developed a generalized stochastic cloud model based on Empirical Orthogonal Functions to generate realistic 3D cloud structure from 2D cloud fields derived from ARM cloud radar and microwave data.

• *Shortwave flux closure experiment at Nauru*. Performed a preliminary shortwave flux closure experiment on three weeks of data for Nauru for Dec. 98 by retrieving water vapor and cloud properties at one minute intervals, performing broadband radiative transfer, and comparing to the ARM surface pyranometer data.

• *Understanding a variety of cloudy power spectra.* Using a great variety of Landsat scenes, we have learned how to characterize 3D cloud structure from power spectra and autocorrelation function [JP 6].

• *Satellite retrieval of cloud optical depth.* A new cloud optical depth retrieval technique that accounts for cloud side illumination and shadowing effects at high solar zenith angles has been proposed and applied to Landsat radiances over the Oklahoma ARM site [JP 7].

• *Albedo bias and horizontal variability in marine stratiform clouds.* Analyzing more than 1500 images of stratiform clouds, we found that instantaneous plane-parallel albedo bias is much smaller than has been previously reported based on long time series of LWP [JP 4].

• *Intercomparison of 3D Radiation Codes (I3RC).* Actively participated in I3RC by serving in a Steering Committee, discussing and developing cases, running our 3D models, analyzing and reporting results of intercomparison [CP 12-16].

• *Impact of unresolved cloud spatial structure on prognostic cloud schemes.* Showed that unresolved cloud spatial structure is likely responsible for much of the required but sometimes unphysical tuning of climate and cloud-resolving model parameters [JP14].

• *Comparison of surface shortwave downward fluxes measurements.*. Coordinated and analyzed the results of a comparison between two different methods and technologies of measuring total solar irradiance (Valero and Dutton) [JP 15].

5. Progress and accomplishments

• *Cloud-Vegetation Interaction*

We have developed robust algorithms that exploit the sharp spectral contrast in vegetation surface reflectance across 700 nm wavelength to retrieve cloud properties from ground-based radiance measurements [JP 10]. Because of the complex three-dimensional (3D) radiative effects of broken clouds, retrievals based on a one-dimensional (1D) inversion technique almost surely fail. However, algebraic combinations of ground radiance measurements at different wavelengths remove the effects of 3D cloud structure which in turn allows a modified 1D radiative transfer algorithm to be successful [CP 2, 10]. To illustrate the above technique, we used downwelling flux at the surface measured by the Shortwave Spectrometer (SWS) at the ARM site in Oklahoma and corresponding Microwave Water Radiometer (MWR) measurements of column-integrated liquid water (LWP). Figure 1 shows a ratio between the difference and the sum of two downwelling fluxes (flux NDCI) on the same plot as cloud liquid water path (LWP) averaged over 1 min. Clearly, flux NDCI is highly correlated with LWP.

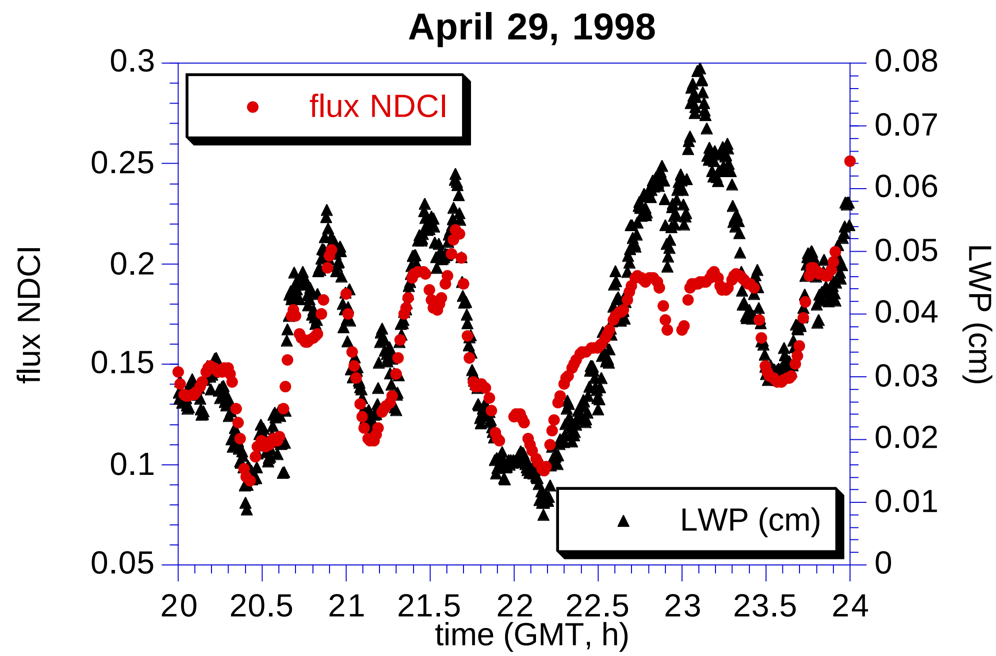


Fig. 1. Flux NDCI and cloud LWP measured at the ARM site in Oklahoma and averaged over 1 min. Flux NDCI is a ratio between the difference and the sum of two downwelling fluxes (per unit incident flux) at 0.67 and 0.87 µm. The poor correlation for about 40 min from 22.7 to 23.3 h is not yet understood.

• *Horizontal radiative fluxes in clouds*

Combining Brownian motion with diffusion theory, we derived simple analytic formulas characterizing horizontal photon transport in clouds [JP 11]. Specifically, we derived the r.m.s. horizontal displacement of reflected photons (ρ) as a function of single-scattering albedo (ϖ_0), asymmetry factor (g), cloud optical (τ) and geometrical (H) thicknesses:

$$\sqrt{\langle \rho^2 \rangle} \propto \begin{cases} \dfrac{1}{(1-\varpi_0 g)^{3/4}(1-\varpi_0)^{1/4}} \dfrac{H}{\tau}, \varpi_0 \to 1, \tau > 1/\sqrt{3(1-\varpi_0)(1-\varpi_0 g)} \\ \dfrac{1}{\sqrt{(1-g)}} \dfrac{H}{\sqrt{\tau}}, \varpi_0 = 1 \end{cases} \quad (1)$$

Figure 2 compares Eq. (1) with Monte Carlo simulations. It allowed us to generalize the theory of "radiative smoothing"—a process determined by multiple scattering and photon horizontal transport—to absorbing wavelengths. Radiative smoothing theory contributes significantly to our understanding of why and when the IPA breaks down [JP 2, 6; CP 4].

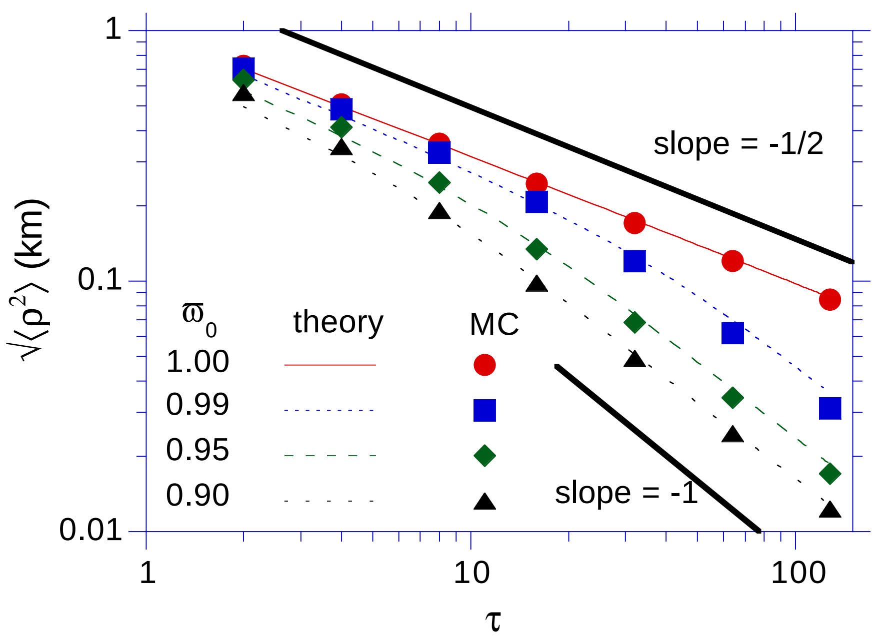


Fig. 2. The root-mean-square horizontal displacement of reflected photons derived analytically (Eq. (1)) and calculated using Monte Carlo (MC) simulations for homogeneous clouds.

Figure 3 shows wavenumber spectra for both IPA and 3D cloud nadir radiance fields simulated by MC method. The IPA radiance fields have the same power-law spectra as the optical depth. The spectra of the 3D radiance fields bend away from this power law below a few hundred meters. This scale-break occurs at the so-called radiative smoothing scale which is where the IPA breaks down. Equation (1) provides a good estimate of these scale breaks.

The results of our theoretical study were applied to Landsat TM observations. We found that TM power spectra are strongly affected by photon horizontal transport. We were able to understand (and simulate) a variety of shapes not shown or explained in previous observational studies [JP 6].

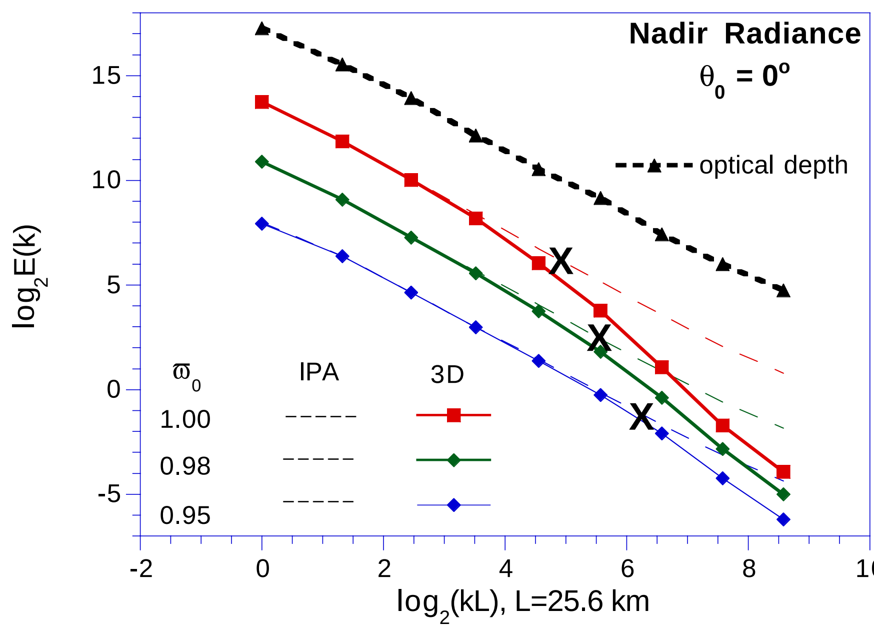


Fig. 3. *Wavenumber spectra for both IPA and 3D nadir radiance fields.* The distribution of cloud optical depth is simulated with 10-step "bounded-cascade" models with $\beta = 5/3$ (upper curve). Cloud mean optical depth is 13, pixel-size is 25 m, cloud top and base are flat, geometrical thickness H is 300 m. Results are averaged over 10 independent realizations. Crosses (**X**) indicate the approximate location of a scale-break. Note that with more absorption the scale break moves towards smaller scales.

- *Retrieval of cloud optical depth.*

We proposed a new satellite or aircraft cloud optical depth retrieval technique that accounts for cloud side illumination and shadowing effects present at high solar zenith angles. We believe this may prove important in testing radar retrievals of cloud optical depth in broken cloud fields. The technique uses the normalized difference of nadir reflectivities (NDNR) at a conservative and an absorbing wavelength. It can be further combined with our inverse Nonlocal Independent Pixel Approximation (NIPA) that corrects for radiative smoothing, thus providing a retrieval framework where all 3D cloud effects can potentially be accounted for. The effectiveness of the new technique was demonstrated using MC simulations. Real world application is shown to be feasible using Landsat-5 Thematic Mapper (TM) radiance observations over the ARM SGP site. The results of retrieval are compared with the LWP inferred from the surface MWR [JP 7].

• *Radar/microwave radiometer cloud retrieval*

We performed vertical cloud property retrievals for three months of Nauru data (12/98 - 1/99 and 6/15 - 7/15/99) and three months of SGP data (12/97 - 2/98). We compared several different cloud property retrieval methods, and found that some were very sensitive to uncertainties in the observed liquid water path or radar reflectivity; often leading to unrealistic retrieved number concentrations. We developed our own vertically integrated retrieval method based on Bayes' theorem, which uses prior knowledge about cloud microphysics from in situ cloud probes and accounts for uncertainties in the observed data. Figure 4 shows that the Bayes method gives more credible results than the Frisch method in this difficult case. The Bayes method combines the MWR and MMCR data in a more optimal way and remains consistent with known microphysics.

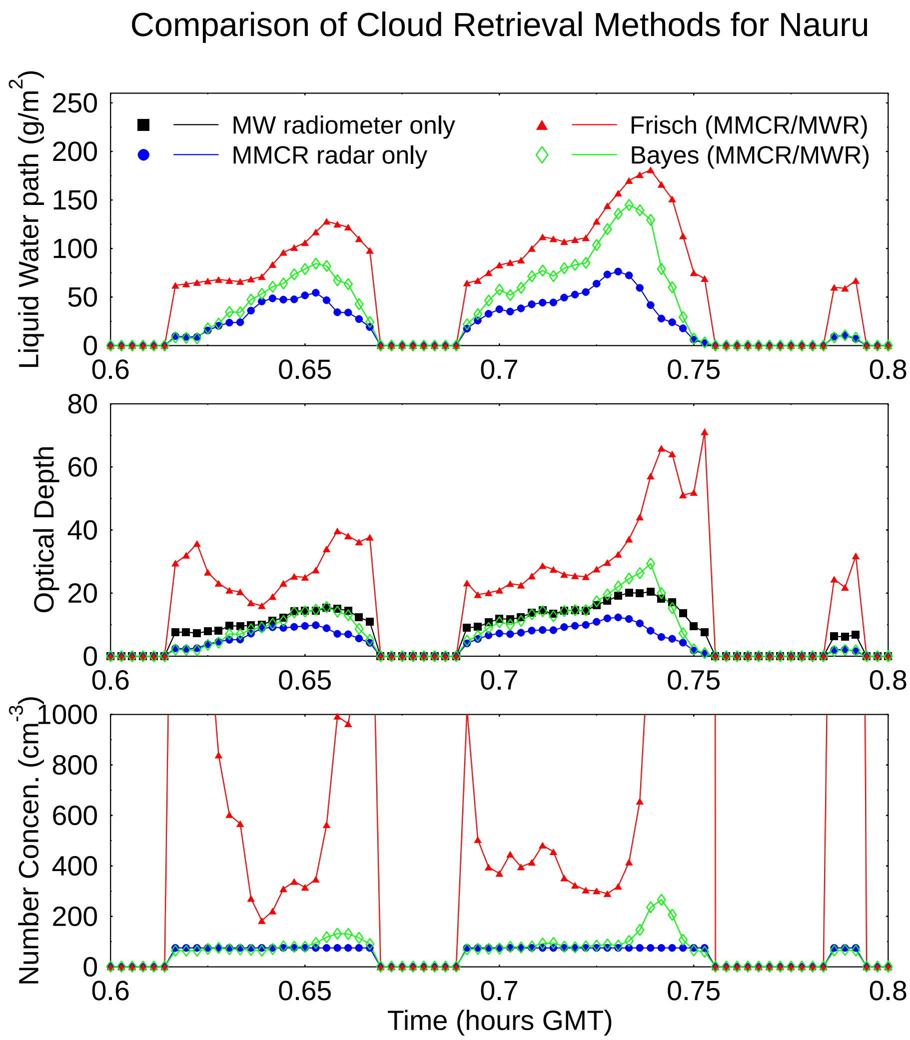


Fig. 4. Comparison of four cloud retrieval methods using the MMCR cloud radar and/or the microwave radiometer (MWR). In these methods, liquid water path (LWP) can be both input and output. The input LWP is from the standard ARM regression algorithm using MWR data, and has a large clear sky offset. The MWR only algorithm assumes an adiabatic profile of liquid water content with 50 droplets/cm^3. The MMCR algorithm assumes a lognormal droplet size distribution with width σ=0.35 and 75 droplets/cm^3. The Frisch method assumes the input LWP is correct and derives the number concentration from the LWP and radar. This leads to unphysical results (e.g. huge number concentrations) at the cloud edges where the radar reflectivity is small. The Bayes algorithm uses a priori information on the joint probability distribution of lognormal droplet distribution parameters obtained from Florida cumulus FSSP data. It also uses specified uncertainties on the MWR derived liquid water path and MMCR radar data.

• *Flux closure experiment at Nauru*

We performed a shortwave flux closure experiment on three weeks of data (12/98) from Nauru. We retrieved one-minute resolution vertical profiles of cloud liquid water content and effective radius from the MMCR and MWR, and atmospheric profiles from radiosondes and the MWR. We performed 1-D broadband solar radiative transfer calculations on the retrieved cloud profiles with Evans' SHDOM model and the correlated k-distribution from the RRTM model (Mlawer 1998). Modeled shortwave downwelling surface fluxes were compared to observed fluxes from the Precision Spectral Pyranometer (PSP) and Normal Incidence Pyrheliometer (NIP). The preliminary results indicate that due to the variability of the clouds at Nauru, tens of hours of data must be averaged to reduce the rms discrepancy between model and measurements to the 20 W/m^2 level.

• *3D stochastic cloud model.*

We developed a stochastic cloud field generation method based on Empirical Orthogonal Functions (EOFs). This method can create realistic random 3D cloud fields using statistics from 2D radar-derived cloud fields and assuming horizontal isotropy. The method generates random fields with the same histogram of extinction and binary (clear/cloud) two point statistics as the original input fields. The stochastic generation algorithm was applied to nonprecipitating cumulus clouds above. Broadband domain average solar radiative transfer calculations show that the 2D stochastic fields are radiatively equivalent to the original 2D radar-derived cloud fields. However, for these small cumulus clouds solar radiative transfer in 2D fields is not equivalent to transfer in 3D fields.

• *Impact of sub-grid scale variability on prognostic cloud schemes*

The representation of clouds in large scale atmospheric models has become substantially more realistic in the past decade with the introduction of prognostic cloud schemes. These schemes explicitly compute the average concentrations of water and ice in the cloudy portion of each grid cell as a time-evolving balance between sources and sinks. The schemes are formulated in terms of average values within the grid cell. In nature, though, concentrations q of cloud water and ice vary at spatial scales down to centimeters. Variability in q generally increases with spatial scale, and at the grid spacings typical of climate models (250 km) the neglected variability can be a substantial fraction of the mean value.

One well-known radiative impact of unresolved spatial variability in climate simulations is a systematic bias in calculated cloud albedo, due to albedo being a convex nonlinear function of cloud optical. But in the presence of sub-grid scale variability, the average rate of *any* process which depends non-linearly on condensate concentration differs from the rate computed using the average concentration. A general framework for computing the bias in process rates due to unresolved sub-grid scale variability in q is described in [JP 14]. The paper also assesses the magnitude of the bias for example distributions, for example of autoconversion rate (cf. Fig. 5). We use observations of liquid water path from the ARM SGP site to show that the presence of sub-grid scale variability is a significant factor driving the current need to tune large scale model parameters in an *ad hoc* and sometime unphysical way.

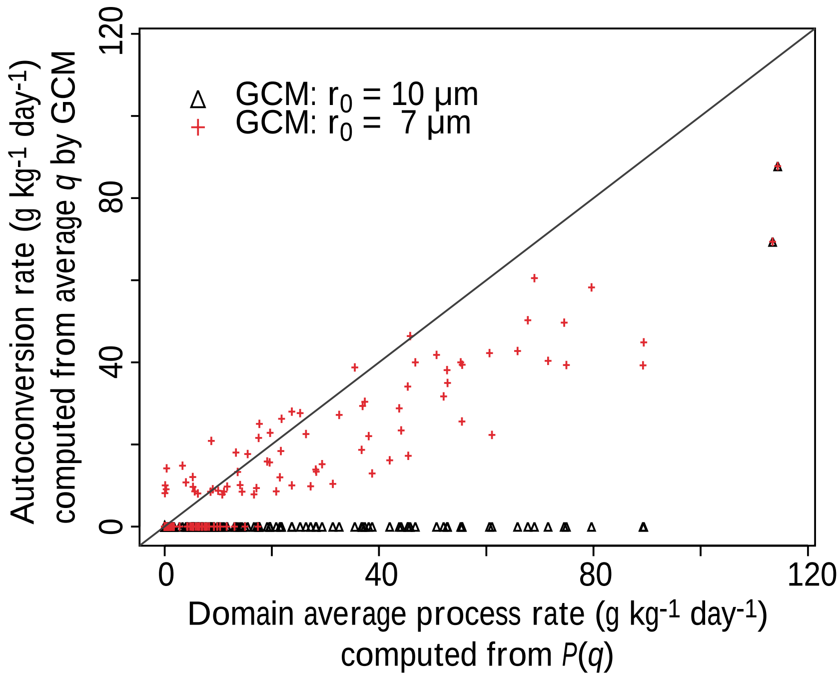
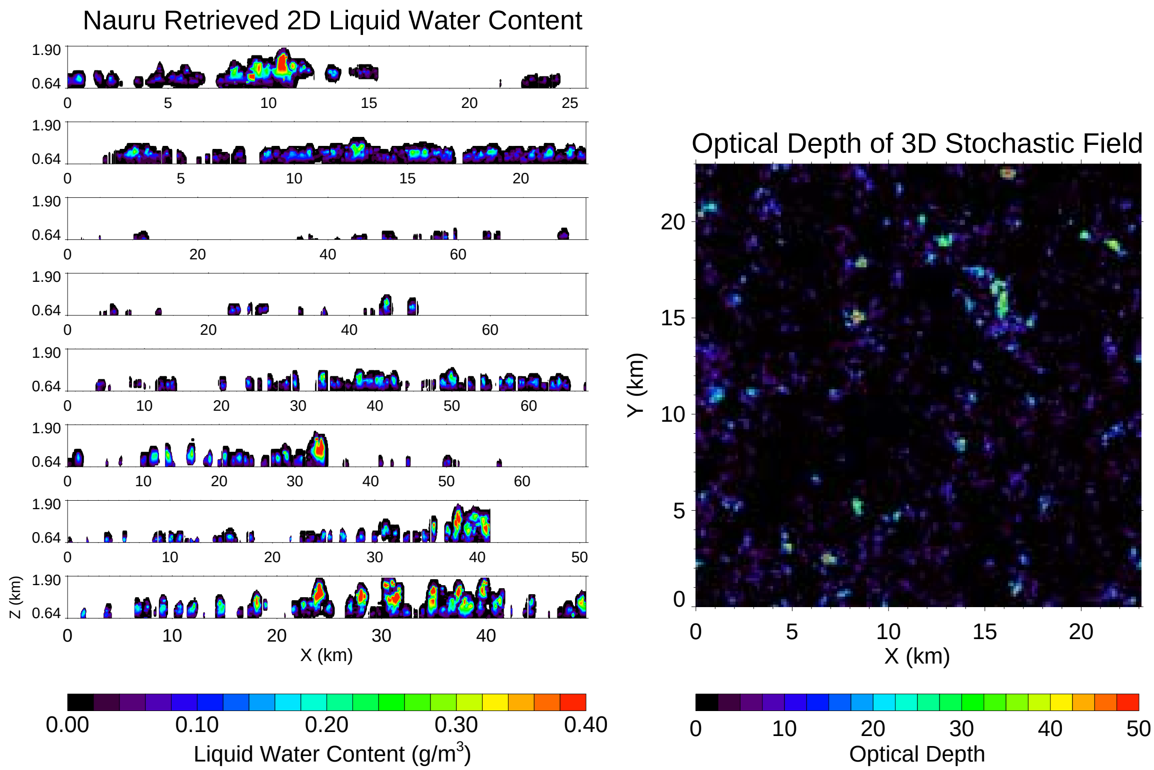


Fig. 5. *Average autoconversion rates computed by a large scale model cloud parameterization.* Autoconversion refers to the rate at which cloud water is converted to rain. Time-height profiles of q are inferred from cloud radar reflectivity measurements made once a minute at ARM SGP. The autoconversion rate is proportional to $q^{7/3}$ once a threshold value of inferred drop radius r_0 is exceeded. Three-hour average autoconversion rates computed with $r_0 = 10$ μm, shown on the x-axis, vary from 0 to almost 100 g kg^{-1} day^{-1}. Autoconversion rates computed from the average value of q alone, however, are always zero. The threshold radius must be reduced to 7 μm (or q reduced by a factor of nearly 2) for autoconversion rates to be accurately computed if only the single time-average value of q is used.



This figure illustrates a new technique for generating random three-dimensional (3D) cloud fields from 2D fields derived from ARM cloud radars. This technique is important because the radiative effect of cloud fields depends on their 3D dimensional structure, while the ARM cloud radars only sample the time-height cross section of clouds as they advect past. The left panel shows eight 2D cloud fields derived from the Nauru radar assuming a log-normal droplet size distribution with fixed number concentration and advecting the clouds by the radar at a speed determined from radiosondes. The right panel shows the optical depth for a single realization of the 3D stochastic cloud field generation method. The statistics of thirty 2D radar derived clouds fields were input to the technique. The stochastic cloud field generation algorithm is based on Empirical Orthogonal Functions (or principal component analysis), and it assumes horizontal isotropy and translational invariance. Broadband domain average solar radiative transfer calculations indicate that 2D stochastic cloud fields are radiatively equivalent to the original 2D radar-derived cloud fields. For these small cumulus clouds, however, the solar fluxes in the 2D fields are quite different from those in the realistic 3D fields. (co-PI: K. Franklin Evans, University of Colorado, 2000)

7. Refereed Publications

ARM-related publications (1999-July 2000)

JOURNAL PAPERS (JP)

[1] Davis, A., Marshak, A., Gerber, H., and Wiscombe, W., 1999. Horizontal Structure of Marine Boundary-Layer Clouds from Cm– to Km–Scales. *J. Geophys. Res.*, **104**, 6123-6144.

[2] Marshak, A., Oreopoulos, L., Davis, A., Wiscombe, W., and Cahalan, R., 1999. Horizontal Radiative Fluxes in Clouds and Accuracy of the Independent Pixel Approximation at Absorbing Wavelengths. *Geoph. Res. Lett.*, **11**, 1585-1588.

[3] Marshak, A., Wiscombe, W., Davis, A., Oreopoulos, L., and Cahalan, R., 1999. On the Removal of the Effect of Horizontal Fluxes in Two-Aircraft Measurements of Cloud Absorption. *Quart. J. Roy. Meteor. Soc*., **558**, 2153-2170.

[4] Pincus, R., McFarlane, S. A., and S. A. Klein, 1999. Albedo Bias and the Horizontal Variability of Clouds in Subtropical Marine Boundary Layers: Observations from Ships and Satellites. *J. Geophys. Res*., **104**, 6183-6192.

[5] Davis, A., Marshak, A., Kassianov, E., and Stokes, G., 1999: Three-Dimensional Radiative Transfer Makes Its Mark. *EoS, Trans, AGU*, **80**, 622 and 624.

[6] Oreopoulos, L., Marshak, A., Cahalan, R., and Wen, G., 2000. Cloud Three-Dimensional Effects Evidenced in Landsat Spatial Power Spectra and Autocorrelation Function. *J. Geophys. Res.*, **105**, 14777-14788.

[7] Oreopoulos, L., Cahalan, R., Marshak, A., and Wen, G., 2000. A New Normalized Difference Cloud Retrieval Technique Applied to Landsat Radiances Over the Oklahoma ARM Site. *J. Appl. Meteor.* (accepted, February 2000).

[8] Knyazikhin, Yu., and Marshak, A., 2000. Mathematical Aspects of BRDF Modeling: Adjoint Problem and Green's Function. *Remote Sens. Review*, (accepted, March 2000).

[9] Gerber, H., Jensen, J., Davis A., Marshak, A., and Wiscombe, W., 2000. Spectral Density of Cloud Liquid Water Content at High Frequencies. *J. Atmos. Sci.*, (accepted, June 2000).

[10] Marshak, A., Knyazikhin, Yu., Davis, A., Wiscombe, W., and Pilewskie, P., 2000. Cloud – Vegetation Interaction: Use of Normalized Difference Cloud Index for Estimation of Cloud Optical Thickness. *Geoph. Res. Lett.*, **27**, 1695-1698.

[11] Davis, A., and Marshak, A., 2000. Multiple Scattering in Clouds: Insights from Three-Dimensional Diffusion Theory. *Nuclear Sci. and Engin.*, (accepted, May 2000).

[12] Cahalan, R. F., Oreopoulos, L., Wen, G., Marshak, A., Tsay, S.-C., and DeFelice, T., 2000. Cloud Characterization and Clear Sky Correction from Landsat 7. *Remote Sens. Environ.*, (submitted, March 2000).

[13] Benner, T. C. and K. F. Evans, 2000. Three-Dimensional Solar Radiative Transfer in Small Tropical Cumulus Fields Derived From High-Resolution Imagery. *J. Geophys. Res.* (will be submitted in July 2000).

[14] Pincus, R., and S. A. Klein, 2000. Unresolved Spatial Variability and Process Rate in Large Scale Models. *J. Geophys. Res*., (submitted, June 2000).

[15] Wiscombe, W., A. Marshak, E. Dutton, D. Nelson, B. Bush, and F. Valero, 2000. Comparison of surface shortwave downward fluxes measured by Radiation Measurement System (RAMS) and world standard cavity + shaded pyranometer combinations. *J. Geophys. Res.*, (will be submitted in July, 2000).

8. Published (either paper or web-based) Extended Abstracts

CONFERENCE PAPERS (CP)

[1] Davis, A., Marshak, A., and Clothiaux, E., 1999. Anisotropic multi-resolution analysis in 2D, Applicattion to long-range correlations in cloud mm-radar fields. In: S.P.I.E. Proceedings, vol. 3723, H. H. Szu [Ed.], pp. 194–207.

[2] Wiscombe, W., Marshak, A., Knyazikhin, Y., Davis, A., and Barnard J., 1999. Retrieving Broken-Cloud Optical Thickness Using Cloud – Vegetation Interaction and a Two-Channel Narrow Field Of View Radiometer. Proceedings of the 9th Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 22-26, 1999, San Antonio (TX), http://www.arm.gov/docs/documents/technical/conf_9903/wiscombe-99.pdf.

[3] Oreopoulos L., Cahalan, R., Marshak, A., and Wen, G., 1999. Cloud optical property retrieval over ARM sites from Landsat. Proceedings of the 8th Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 23-27, 1998, Tucson (AZ), U.S. Department of Energy, pp. 545-549.

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[5] Oreopoulos, L., A. Marshak, R. Cahalan, and G. Wen, 1999. Behavioral changes of observed and simulated cloud power spectra with solar zenith angle and wavelength: implications for cloud optical property retrievals. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. 68-71, AMS, Boston (Mass).

[6] Davis, A., Pfeilsticker, K., and Marshak, A., 1999. The Levy-flight model for solar photon transport in the cloudy atmosphere: observational support from high-resolution oxygen a-band spectroscopy. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. 575–578, AMS, Boston (Mass).

[7] Evans, K. F., S. McFarlane, and W. Wiscombe, 1999. Three-Dimensional Radiative Transfer Effects of Two-Point Statistical Representations of Broken Cloud Structure. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. 579–582, AMS, Boston (Mass).

[8] Benner, T. C. and K. F. Evans, 1999. Three-Dimensional Broadband Solar Radiative Transfer in Small Tropical Cumulus Fields Derived From High-Resolution Imagery. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. 438–441, AMS, Boston (Mass).

[9] Zuidema, P. and K. F. Evans, 1999. An evaluation of the tilted independent pixel approximation for tropical fair-weather cumuli observed by cloud radar. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. 327–330, AMS, Boston (Mass).

[10] Wiscombe, W., Marshak, A., Knyazikhin, Y., and Davis, A., 2000. The Use of Reflection from Vegetation for Estimating Broken-Cloud Optical Depth. Proceedings of the 10th Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio (TX),

[11] Marshak, A., A. Davis, L. Oraiopoulos, and T. Várnai, Error Estimation in the Monte Carlo Method for Simulating Solar Radiances; Illustration with Cloud Models Based on Landsat Measurements, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[12] Evans, K. F., and L. H. Chambers, SHDOM, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[13] Marshak, A., A. Davis, L. Oraiopoulos, and T. Várnai, Error Estimation in the Monte Carlo Method for Simulating Solar Radiances; Illustration with Cloud Models Based on Landsat Measurements, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[14] Várnai, T., R. Davies, and A. Marshak, A Monte Carlo model of 3D radiative transfer, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[15] Davis, A., Z. Qu, Approximation of 3D radiative transfer in clouds with diffusion theory, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[16] Davis, A., Discrete-angle radiative transfer: Improving on diffusion theory, in *Proceedings of the Intercomparison of 3-D Radiation Codes*, November 17–19, 1999, Tucson, AZ, 2000.

[17] Evans, K. F., S. McFarlane, and W. Wiscombe, 2000: A Stochastic Cloud Field Model for Generalizing Radar Derived Cloud Structure for Solar Radiative Transfer Calculations. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio, Texas.

[18] McFarlane, S. A. K. F. Evans, E. J. Mlawer, and E. E. Clothiaux, 2000: Shortwave Flux Closure Experiments at Nauru. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio, Texas.

9. Please update us on the status of submitted referred publications from the previous FY progress report. (If none, note "NONE").

See above: JP 7, 8, and 9. Papers JP 7, 8 are in press, paper JP 9 is still under review.